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BACHELOR'S THESIS

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BRNO UNIVERSITY OF TECHNOLOGY
VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION
FAKULTA ELEKTROTECHNIKY
A KOMUNIKAČNÍCH TECHNOLOGIÍ

DEPARTMENT OF FOREIGN LANGUAGES
ÚSTAV JAZYKŮ

LIFE MANAGEMENT OF POWER OIL TRANSFORMER
ŘÍZENÍ ŽIVOTNOSTI VÝKONOVÉHO OLEJOVÉHO TRANSFORMÁTORU

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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VEDOUCÍ PRÁCE

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VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ

Bakalářská práce

bakalářský studijní obor **Angličtina v elektrotechnice a informatice**

Ústav jazyků

Studentka: Karolína Čechová ***ID:*** 203146
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NÁZEV TÉMATU:

Řízení životnosti výkonového olejového transformátoru

POKYNY PRO VYPRACOVÁNÍ:

Základním cílem práce je popsání procesu řízení životnosti a degradačních mechanismů ovlivňujících životnost výkonového olejového transformátoru během jeho provozu. Praktická část bude zaměřena na zhodnocení životnosti vybraného výkonového olejového transformátoru.

DOPORUČENÁ LITERATURA:

Cvešpr P. Integrované řešení diagnostiky výrobního zařízení v české energetice, Metodika - ČEZ

Chakravorti S., Dey D, Chatterjee B. (2013), Recent Trends in the Condition Monitoring of Transformers: Theory, Implementation and Analysis (Power Systems), Springer, ISBN-13: 978-1447155492

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Abstract

To understand the significance of the life management process concerning power oil transformers, at first, it is essential to realise their role in the electrical grid. They are primarily used to interface step up and step down voltages in the transmission and distribution system according to the contemporary needs. The unreliability of power oil transformers can disrupt the stability of the electric power supply, which represents significant economic and technical losses for companies that manage this type of equipment. Therefore, I decided to write a thesis that provides an overview about the life management process by describing its economic benefits along with technical diagnostics, which help to identify incipient defects at their early stages that may arise during the operation of power oil transformers. The main aim of this thesis is to describe and prove the importance of the life management process itself and the need to analyse transformer parameters by diagnostic methods to detect possible defects. The practical part of the thesis focuses on proposing the most suitable diagnostic methods for measuring the selected parameters of the chosen power oil transformer. The selected parameters are then analysed, and the overall condition of the chosen power oil transformer is estimated.

Keywords

Life management, power oil transformer, technical diagnostics, degradation mechanisms, diagnostic methods

Abstrakt

Pro pochopení významu procesu řízení životnosti výkonových olejových transformátorů, je nutné si nejdříve uvědomit jejich roli v elektrizační soustavě. Používají se především ke zvýšení a snížení napěťových úrovní v přenosové a distribuční soustavě dle aktuálních potřeb. Nespolehlivost výkonových olejových transformátorů může způsobit narušení stability dodávky elektrické energie, což představuje značné finanční a technické ztráty pro společnosti, které spravují tento typ zařízení. Z tohoto důvodu jsem se rozhodla napsat práci, která poskytuje přehled o procesu řízení životnosti, popsáním jeho ekonomických přínosů spolu s technickými diagnostikami, které napomáhají ke zjištění vznikajících poruch během provozu výkonových olejových transformátorů. Hlavním záměrem této práce je popsat a dokázat důležitost procesu řízení životnosti a využití diagnostických metod ke sledování parametrů transformátoru, které slouží jako prostředek ke zjištění možných poruch. Praktická část je zaměřena na navržení vhodných diagnostickým metod pro měření zvolených parametrů vybraného výkonového olejového transformátoru. Poté je provedena analýza zvolených parametrů a na základě jejích výsledků, je určen celkový stav vybraného výkonového olejového transformátoru.

Klíčová slova

Řízení životnosti, výkonový olejový transformátor, technická diagnostika, degradační mechanismy, diagnostické metody

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Prohlášení

Prohlašuji, že bakalářskou práci na téma *Řízení životnosti výkonového olejového transformátoru* jsem vypracovala samostatně pod vedením vedoucího bakalářské práce a s použitím odborné literatury a dalších informačních zdrojů, které jsou všechny citovány v práci a uvedeny v seznamu literatury na konci práce.

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V Brně dne ....

Karolína Čechová

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Contents

Introduction

Nowadays, with increasing demand for reliable electric power supply, it is vital to secure electrical power transmission and distribution more than ever. It is significantly influenced by the reliable operation of power oil transformers that belong to one of the most important elements, which ensure that the generated electric power reaches end-consumers.

During operation, a power oil transformer is subjected to different stresses, which may affect transformer components by certain degradation mechanisms that increase the probability of failure. Some failures can appear due to natural ageing of transformer materials, especially when the transformer exceeds a designed lifecycle, the possibility of defects is increased to a great extent. In the event of a transformer failure or accident, the stability of electric power supply can be disrupted, which may bring several consequences, e.g. dysfunction of electrical infrastructure, economic and technical losses for companies that manage this type of equipment. It can also lead to permanent damage because the transformer accident is often linked to an explosion, fire, and other possible environmental damage. Financial expenses due to unexpected transformer failure can exceed its initial price several times over. These expenses do not only cover the replacement of the malfunctioned components but also include charges for not providing enough electrical power to end-consumers.

Therefore, it is essential to monitor the condition of power oil transformers continuously in order to prevent and reduce the number of unplanned failures. Implementation of continuous monitoring helps to determine transformer condition by providing up-to-date information about its current state. This process, combined with diagnostic methods, which are used for detection of incipient defects, provides an effective way of ensuring reliable operation of power oil transformer. Continuous monitoring, along with diagnostic methods form just a small part of the process, known as life management.

In this thesis, the benefits of the life management process are described. Additionally, the impacts of degradation mechanisms on selected transformer components are demonstrated. The emphasis is placed on the utilisation of diagnostic methods used to analyse transformer parameters and their possible defects. The practical part of the thesis focuses on the analysis of the chosen power oil transformer and estimating the condition of the insulation system. For this purpose, the set of diagnostic methods is suggested for measuring the selected parameters.

1 Power Transformers

Transformers can be defined as non-rotary AC machines which are operating on the principle of electromagnetic induction (Měřička, Haňka). The invention of the transformer has been very important for the development of electro energetics because it replaced previously used rotating voltage converters (Majling, 2015). In other words, it facilitates the conversion of the AC voltage size. The alternation of voltage level serves for transmitting and distributing electrical power. The increase in voltage leads to a reduction in electric energy losses during the process of transmission. In contrast, the decrease in voltage tends to be used for power distribution and power supply of electrical equipment.

Power transformers are used to interface step up and step down voltages in the transmission and distribution systems. Electrical energy is transferred through electromagnetic induction without any frequency change. Usage of power transformers enables alteration of voltages to a suitable level on each segment of the power transmission and distribution from generation to the end-user (2014). Power transformers are needed at every point where it is required to either step up or step down the voltage in the electrical grid, as Figure 1 indicates. Therefore, they belong among the indispensable equipment of the electrical grid.

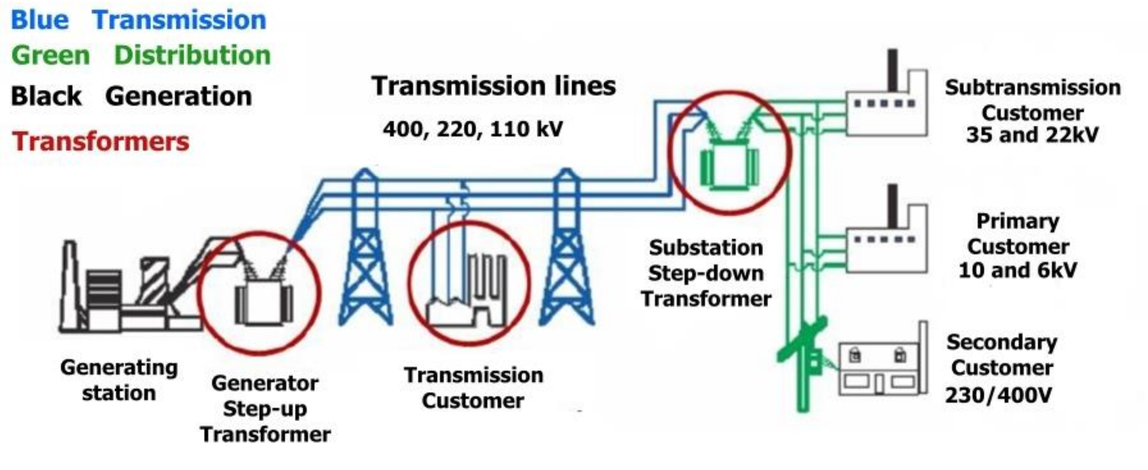


Figure 1 Electric grid representation

The basic structure of the power transformer consists of a magnetic core, windings and bushings, as Figure 2 illustrates. The role of the magnetic core is to provide a path for magnetic flow. The magnetic core is wrapped with a conductor coil that is insulated with pressboard and screens. Windings provide a path for electrical current in the different phases of the power transformer. In the case of the single-phase transformer, two windings are present. The one is connected to a voltage source and creates a magnetic flux that is known as a primary winding. In the secondary winding, a voltage is induced as a result of mutual induction. The difference between output and input voltage in windings determines if a power transformer is used to interface step-up or step-down voltage, e.g., output voltage in the secondary winding is less than the one on the primary winding, which means that the transformer is the step-down type and the other way around. Bushings pass current at a high voltage between the outer and the inner conductors through tank walls.

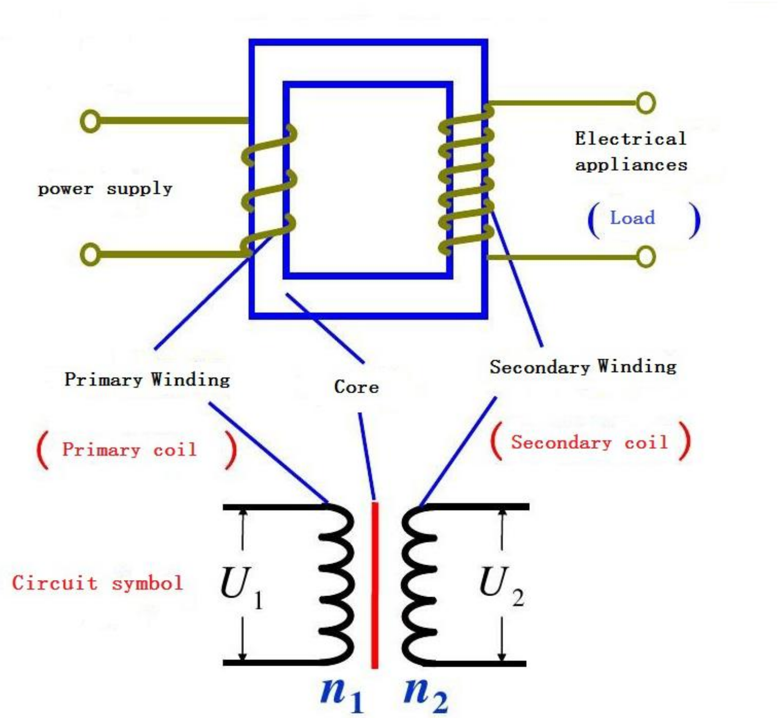


Figure 2 Basic structure of transformer

The design of power transformers differs according to which cooling, and insulation systems are used. With respect to their design, they can be divided into oil-immersed and dry-type transformers.

1.1 Oil-immersed transformers

Oil-immersed transformers belong to the most widely used type of equipment in the electrical grid due to their simple structure, reliable operation and rich manufacturing (2014). Figure 3 represents the typical oil-immersed power transformer. Designed lifecycle is around 30 years (Hrbek, 1966). Perhaps the most significant advantage of the oil-immersed power transformer is the fact that they can operate with higher ratings than dry-types (Larson, 2017). The characteristic feature of the oil-immersed transformer is an oil conservator. The oil conservator monitors the level of oil in the tank and provides the space for thermal expansion of the oil (Electric4U, 2018). It also serves as a reservoir for insulating oil.

Figure 3 Oil-immersed power transformer

The oil represents an essential part of the oil-immersed transformer. In most cases, highly-refined mineral oil is used as insulating oil (2018). This type of mineral oil possesses a great electrical insulating property and can sustain high temperatures. Regardless of the type of oil, it still offers better cooling properties than dry-types because the oil represents a more thorough medium for cooling applications (Larson, 2017). This type of cooling mechanism is highly efficient, and apart from that, it also translates into a smaller, more compact unit. The mineral oil also isolates active parts of the transformer (core and windings), which are immersed in it. However, the main function of the oil is to dissipate the heat that is formed in surplus (Electrical4U, 2019), especially when in-service transformer sustains excessed temperatures.

In-service transformer generates heat that needs to be transmitted from oil to metal shell and afterwards emitted. The temperature must be kept low under all circumstances, in order to preserve the quality of the insulating oil. Therefore, the condition of oil should be periodically analysed and monitored. In practice, the temperature is monitored from the upper layer of oil by thermal sensors, which are embedded in the transformer tank. The average temperature of oil during operation is around 95℃ (GlobeCore). Another important property of insulating oil is the ability to prevent oxidation of the cellulose-made paper insulation to a certain level (Electrical4U, 2019). It helps to separate the atmospheric oxygen and the cellulose by acting as a barrier, thereby minimising the level of oxidation.

However, the insulating oil itself is more susceptible to flammability due to lower heat resistance. The ignition point of the insulating oil is at 275℃ and autoignition around 311℃ (Knebl, 2015). Therefore, additional requirements may be needed in order to use the insulating oil as the cooling medium, especially if transformers are situated in the buildings. For instance, as prevention against oil leakage and spread of fire, oil storage pool facilities must be placed in the area near the transformer (Knebl, 2015). The oil leakage represents a significant concern for the environment because of the non-degradable nature of the oil (SETF). Fire barriers and storage tanks in transformer substation are designed with respect to the flammability and liquidity of the insulating oil. Therefore, the overall construction investment in the fire preventions of each substation is significantly high (apogeeweb, 2019).

1.2 Dry-type transformers

Dry-type transformer, as the name implies, refers to the fact that the air serves as natural ventilation for cooling the system instead of using flammable liquids. Implementation of dry-type transformers proved to be very useful for indoor locations and areas that are more susceptible to fire-related risks (Electrical4U, 2018), as Figure 4 indicates. Thus, they can be installed closer to the target location, e.g., hospitals, airports. Dry-type transformers work on the same principle of electromagnetic induction as other types of transformers.

Figure 4 Dry-type power transformer

They are primarily composed of iron core and windings that are encased in epoxy resin. The epoxy resin helps to protect transformer windings against dust and corrosion (GlobeCore). Since the air is used as the cooling medium, transformer units may operate at higher temperatures because the temperature of the air can be easily affected by the surrounding environment. It may eventually result in their shorter lifecycle, which is from 15 to 25 years (Larson, 2017). Temperature is monitored by the sensors that are embedded in the transformer body in advance together with fans that are designed to dissipate heat. Data obtained from the sensors are related to the specific position because each sensor is fixed to the different measuring point in the transformer body. Due to the fixed position of sensors, the local concentration of heat may occur (GlobeCore). Therefore, the temperature that is reflected by the sensors might not be the accurate temperature of the transformer.

One of the main reasons why the transformer operators prefer dry-type transformers instead of oil-immersed ones is the opportunity to reduce expenses for the overall process of maintenance (Knebl, 2015). Due to missing oil medium, they are considered to be less demanding in terms of periodical monitoring and analysis than oil-immersed transformers (GlobeCore). It significantly reduces investment connected with daily maintenance, fire-related preventions and installation. However, the lack of maintenance for this type of equipment may result in severe consequences. Therefore, keeping the dry-type transformer in the top working condition requires continuous monitoring as well.

Both types of power transformers serve extensively for power distribution. The usage of each type mainly depends on the specific requirements of the target location, end-user, safety regulations and total budget. Although these differences are considered to be a general rule, some exceptions exist. For instance, many manufactures of power oil transformers are making significant progress in the development of naturally degradable fluids, e.g., veggie oils, animal fat (Relectric, 2016). It can reduce the impact on the environment in case of oil leakage and still remain more efficient than dry-type transformers. Since the oil-immersed transformers belong to the most widely used type in the electrical grid, it is the main reason why they will be further analysed.

2 Life management of power oil transformers

As had been already mentioned in the previous chapter, power transformers play a key role in the electrical grid. They are used to interface step up and step down voltages in the transmission and distribution systems. Power transformers transfer electrical energy through electromagnetic induction without any frequency change. Their usage enables alteration of voltages and currents to actual needs. The unreliability of power transformers does not affect only electric power supply but also cause economic and technical losses along with significant environmental consequences. The need for reliable electric power supply more than justifies the main reason why power transformers should be continuously monitored.

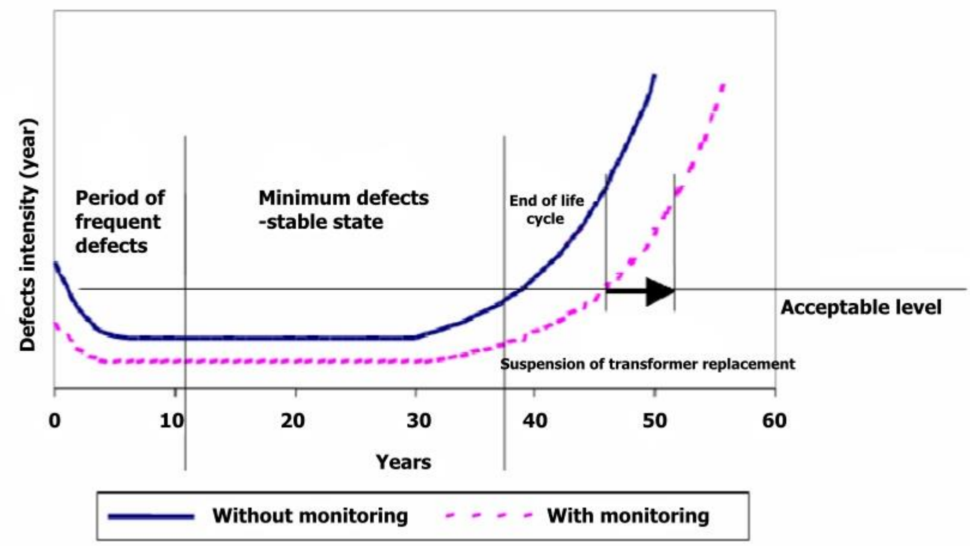


Figure 5 Application of continuous monitoring

The continuous monitoring helps to identify potential defects at their early stages. Preventive actions may be then implemented in time, thereby contributing to the extension of transformer lifecycle, as Figure 5 indicates. Power oil transformer is a very complex and expensive device whose unplanned outage brings severe economic consequences. Accurate and eventually controlled overload operation of power transformer leads to greater efficiency and thus to higher economic profits. In order to prevent and reduce the number of unplanned failures, the power transformer needs to be continuously monitored (Straka, 2008).

Failures in the transmission and distribution systems account for 90% of all-electric power supply problems. Therefore, improving the reliability of individual elements in these two systems can be regarded as a key factor in securing the stability of the electric power supply (Brown, 2002). The power transformer belongs to the essential elements in the electrical grid due to its substantial cost (up to 60% of a substation cost (Franchek, 2003)).

Financial expenses due to unexpected transformer failure can exceed its initial price several times over. The initial price for a new transformer is around tens of millions of crowns as well as financial expenses for not providing enough electrical energy to consumers. These financial expenses do not only cover replacement of the malfunctioned components and cleaning site but also loss of profits and possible deterioration in the quality of electric power supply. According to years of experience and final CIGRÉ reports, which suggest that the transformer life is mostly without a need for maintenance, as is presented in Figure 6.

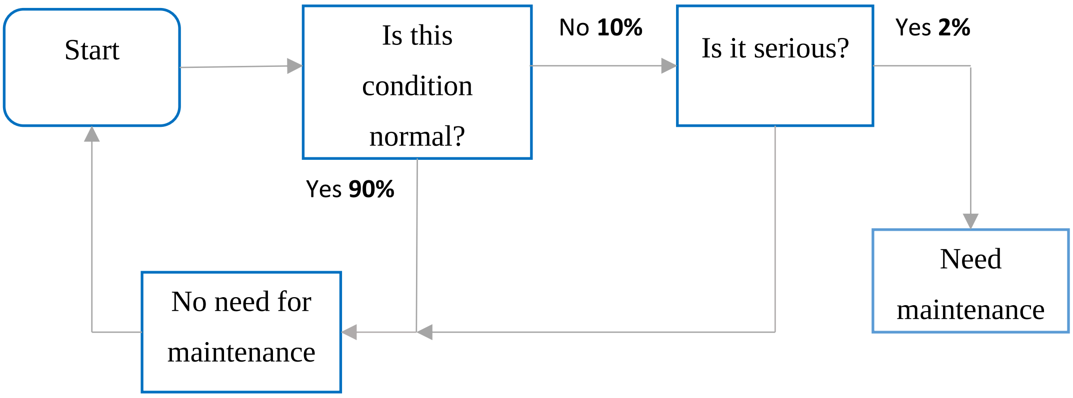


Figure 6 Condition monitoring

A failure of one power transformer may not only result in a disruption of the electric power supply but also increase the load on other transformers connected in the system. If there happen to be insufficient back-up capacities, it must be decided whether or not to allow the overload of other transformers. However, this may lead to a reduction in the service life of individual parts of the transformers. Moreover, it may increase the probability of their failure during the next overloading.

The life of the transformers can often be defined as the period from their manufacture to the date in which the mechanical strength of the insulation system decreases to 50 per cent of its original value (Hrbek, 1956). The designed lifecycle of power transformers is around 30 years. The insulation system is primarily affected by the thermal ageing of the material. The intensity of the disturbances increases exponentially with the temperature. The temperature is not directly proportional to overloading. Thus, the thermal inertia of the casing, windings, core, and oil allows the overloading over a specific period without affecting the lifecycle of transformer parts if the temperature is below the nameplate rating. Despite that, extreme overloading can lead to extreme pressure or even rupture of a transformer tank.

All things considered, the power transformers need to be subjected to technical diagnostics at regular intervals in order to prevent incipient defects, which may arise during their operation. Operators use a mix of surveillance, maintenance, and diagnostic methods as the prime means of life management. Figure 7 provides an overview of the power transformer lifecycle phases, and as can be seen, life management comprises many elements which needs to be considered during the overall process.

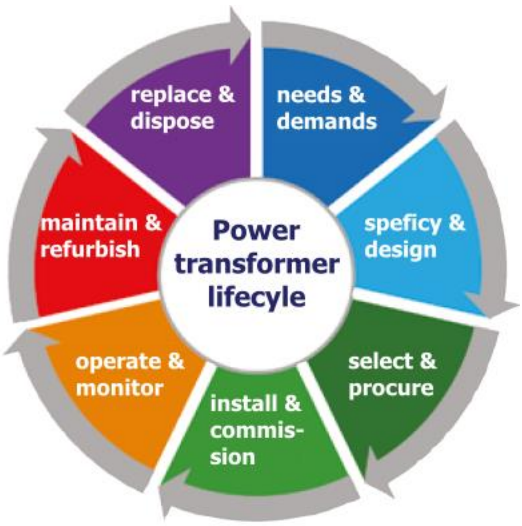


Figure 7 Overview of the power transformer lifecycle phases

Thus, it is beneficial to establish a unified system for collecting data about monitored equipment and interconnect it with the evaluation process that will help to determine proper maintenance. Recorded data from life assessments must be uploaded to the system in order to obtain an excellent service record with little or no degradation history to date. In addition, an appropriate set of technical diagnostics is required to cover all essential parameters of the power transformers.

3 Technical diagnostics

Technical diagnostics provide the necessary up-to-date information about the technical condition of the monitored device. It serves as a useful instrument for the detection of undesirable defects together with their causes. As a result of technical diagnostics is the evaluation of the tested device serviceability along with exposure and localisation of its defects. Technical diagnostics can be divided into online and offline diagnostics.

3.1 Offline diagnostics

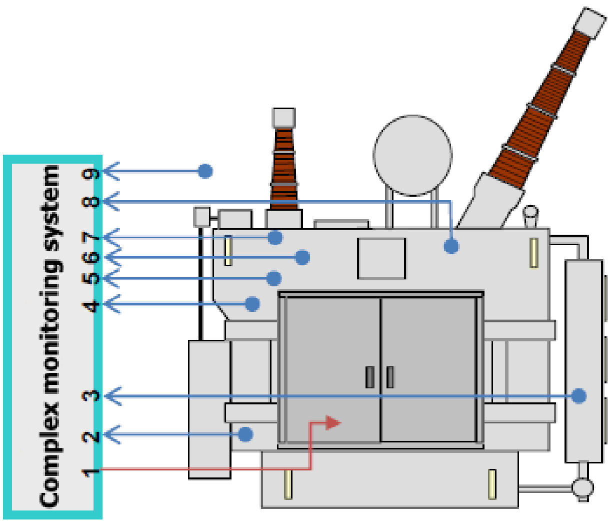
Offline diagnostics are performed on devices that are out of service. Diagnostics are focused on one of the selected transformer parameter. The insulation system represents the most significant source of defects (Cvešpr, 2012), which is the main reason why most diagnostic methods aim in this direction. Measured quantities are, e.g.:

- Oil quality – moisture content in oil, acidity index, dissolved gas-in-oil analysis
- Partial discharges
- Insulation resistance
- Bushings condition

3.2 Online diagnostics

In contrast, online diagnostics obtain data during operation by using sensors located on the diagnosed transformer. Figure 8 provides an overview of sensors situated on a transformer. The main advantage of online diagnostics is the fact that the monitored transformer is continuously under surveillance. Data obtained from online diagnostics are automatically evaluated, and this also contributes to the early detection of undesirable defects. On the other hand, the technical and financial demands are considerably higher and need to process more data than in the case of offline diagnostics. Online diagnostics are used to measure fundamental quantities like, e.g.:

- Return voltage and polarisation current
- The temperature of oil and windings
- Oil quality – water content in oil, dissolved gas-in-oil analysis



Legend:

1) Temperature of lower oil layer
2) Alarms
3) Cooling stage satus
4) Position of tap-changer
5) Interior temperature
6) Dissolved gasses
7) Temperature of upper oil layer
8) Dissolved moisture
9) Ambient temperature

Figure 8 Sensors on the power transformer

4 Degradation mechanisms

The power transformer consists of several components. They are affected by certain degradation mechanisms during their lifecycle. Each of them is influenced differently. Thus, before diagnosing and monitoring the power transformer components, it is essential to understand the abnormal conditions which they may be subjected during their lifecycle. For the manifestation of degradation mechanisms were selected the following components:

1) **Windings** – The main function of the windings is to provide a path for electrical current in the different phases of the power transformer. Windings are subjected to mechanical, thermal, dielectric stresses. Defects on windings can be regarded as one of the most frequent causes of failures in the power transformers.
2) **Magnetic circuit –** Magnetic circuit is not included in the life managing process as a limiting element. It can be a possible carrier of a thermal defect, which may influence the lifecycle of the insulation system paper/oil (Cvešpr, 2012).
3) **Bushings –** Bushings pass current at a high voltage between the outer and the inner conductors through tank walls. Degradation of bushings parameters may be affected by the presence of the partial discharge and the loss of their dielectric properties which leads to overheating.
4) **Insulation system paper/oil –** Insulation system is considered to be the key component in the power transformer (Skála, 1964). It is subjected in large extent to degradation mechanisms (e.g. electric, thermal, mechanical, and environmental) which are mainly affecting the insulating properties. Any defect in the insulation system can trigger a maximum number of defects and result in the reduction of transformer lifecycle.

Diagnostic methods should, therefore, focus on the components mentioned above to prevent the most significant number of defects in the power transformers. Temperature and dissolved oil-in-gases can be regarded as appropriate parameters to monitor from non-electrical elements. These parameters sensitively react to specific defects, which may be, for instance, the formation of sediments and sludge. It can result in the deterioration of the cooling system. Another problem, which could arise is partial discharges and local overheating, which may lead to the heat overloading of individual components as well as the formation of gases.

From electrical quantities should be monitored mainly operating parameters such as current and voltage. Based on evaluating data from continuous monitoring is possible to analyse the electric properties of the oil. Regarding data acquired by continuous monitoring, further diagnostics can be performed in order to provide more accurate data about the transformer condition. Gas chromatography, together with temperature and infra-red test, represent frequently applied diagnostic methods for this purpose.

5 Diagnostic methods

Effective usage of diagnostics methods can help to determine incipient defects at their early stages, thereby contributing to the reliable operation of power transformers. Selected diagnostic methods for demonstration of their application are the following: Dissolved gas-in-oil analysis (DGA), Frequency response analysis (FRA), Moisture analysis, Partial discharge (PD) measurement, Acid or neutralisation number (NN), Interfacial tension (IFT), Oil quality index (OQIN), Furan analysis.

5.1 Dissolved gas-in-oil analysis (DGA)

The main purpose of dissolved gas in oil analysis is to detect gases that are generated due to thermal degradation of the insulation system within the transformer. The main reason why to conduct gas analysis is to provide an indication of abnormal electrical or thermal activity inside the transformer. Decomposed gases occur during defects, which are typically formed due to degradation of the insulation system and decompose the oil into hydrocarbons and carbon oxides gases which can be detected by DGA. These gases may be formed as a result of either corona or partial discharge, thermal decomposition, sparking and pyrolysis (Šišić, 2015). Most of the energy is released during sparking, followed by overheating and corona. The level and ratio of decomposed gases serve as a good indicator for the detection and identification of incipient defects.

In practice, nine gases are measured in the oil sample and analysed by a sophisticated technique of gas chromatography or gas separation. The extracted gases in oil sample are the following: nitrogen, oxygen, carbon monoxide, carbon dioxide and five hydrocarbon gases hydrogen, methane, ethane, ethylene, and acetylene. The concentration of these gases represents an essential opportunity for determining potential defects (Šišić, 2015). The relative amount of gases is strongly dependant on temperature, thereby providing the possibility to distinguish defects by the relative concentration of different gases in the oil. Generally, some of these gases are found to be emitted in a large extent if the internal temperature rises to a certain level (e.g. hydrogen and methane at 110℃, ethane at 150℃, ethylene at 300℃, acetylene at 700℃) (Young and Rodriguez). The absolute value for each gas is considered together with the ratio of gases, which is examined in order to provide information about the type and severity of the defect. Table 1 illustrates IEEE limits for dissolved gasses in transformer oil.

Gas	**IEEE Limit* (ppm)**	**Age compensated (n=years in service)**	**Interpretation**
Hydrogen	100	20n+50	Arcing, corona, cellulose degradation
Methane	120	20n+50	Partial discharge, local overheating
Ethane	65	20n+50	Local overheating
Ethylene	50	20n+50	Severe overheating
Acetylene	35	5n+10	Electrical arcing
Carbon monoxide	350	25n+500	Severe overloading
Carbon dioxide	2500	100n+1500	Severe overloading

Table 1 IEEE Limits for dissolved gasses in transformer oil

However, during regular operation, when the thermal and electric stresses are not significantly high, the decomposed gases possess enough time to dissolve themselves in the insulation oil (Electrical4U, 2019). Some gassing rates are expected to rise during the normal ageing process of insulation oil. Therefore, it is essential to differentiate between excessive and regular gassing rates.

The DGA test is preferred to be conducted periodically (Neumann, 2006) to receive up-to-date information about the condition of the insulation oil over transformer lifetime. The dissolved gasses in the transformer oil are frequently analysed by gas chromatography, which is considered to be one of the most important and sensitive methods for early detection of changes in the state of the insulation system, thereby representing an excellent indicator of the incipient defects (Šišić, 2015). It is necessary to emphasise that gases in the oil are formed only in the in-service transformer. Therefore, samples should be extracted during service or soon after the transformer has been shut down (Šišić, 2015). In order to successfully analyse the composition of gases in the oil, samples are extracted from the oil by hermetically sealed glass syringes to avoid exposure to air and sent to the laboratory as soon as possible.

The gas chromatography is based on the principle of heating the column of the chromatograph to a certain temperature at which is further maintained (Ertl, 2012). Temperature is maintained by an oven that keeps the temperature at an optimum level, thereby improving the separation process. The oven can operate at a wide temperature range (5℃ – 400℃), but usually, the temperature needed for the process is less than 250℃ (Šišić, 2015). A fan is embedded in the oven and ensures even level of temperature throughout the oven. A carrier gas is then injected into the column at a constant speed with the sample. The individual component of the sample is decelerated by the stationary phase of the column and subsequently detected at the exit by the detector. The size of the deceleration can be used to determine which component of the sample is involved, as Figure 9 illustrates.

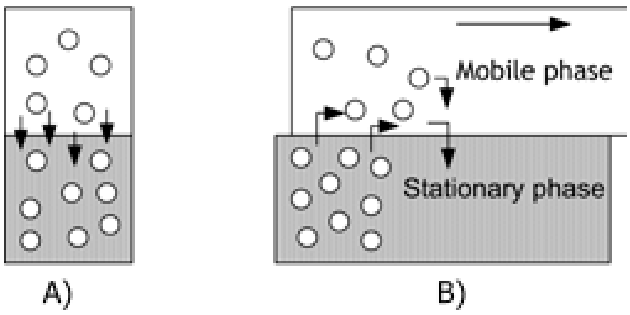


Figure 9 Distribution between the two phases

A) Equilibrium of molecules between stationary phases

B) Model of chromatographic process

The gas chromatograph is defined as an analytical instrument that is used to measure the content of different components in a sample. The instrument is divided into several units which are supported by microprocessor systems and temperature controllers (Šišić, 2015). The oil sample is injected into an instrument where enters a gas stream, which transports the sample into a separation tube, also known as a column. Components present in the oil sample are separated inside the column. The quantity of components is measured by a detector when they exit the column. The temperature in the detector should be higher than in the column in order to avoid condensation of the sample (Ertl, 2012). The detector emits a signal that mainly depends on components exiting the column and is recorded in a computer and printed in the form of the chromatogram, as Figure 10 illustrates. However, in order to measure a sample that contains an unknown concentration of gases, it is necessary to inject another sample with a known concentration into an instrument. The concentration of gases in the oil sample can be then calculated by comparing a standard peak retention time and area with the test sample.

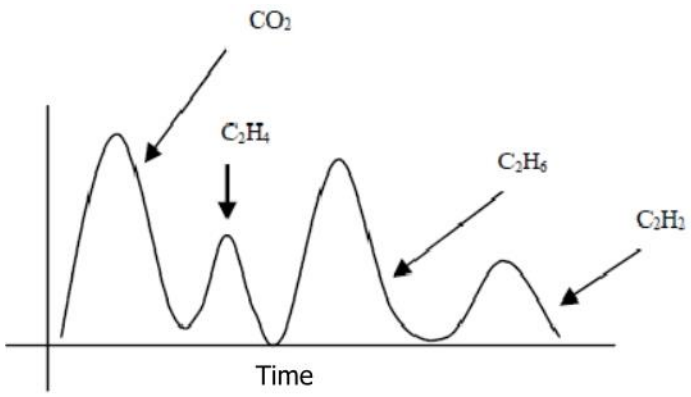


Figure 10 Example of result from chromatogram

DGA is regarded as a very reliable method for the detection of incipient defects in power oil transformers. By examining the percentages of decomposed gases presented in the oil, DGA provides insight into thermal and electrical stresses sustained by the power transformer, thereby helping to prevent further damage.

5.2 Frequency response analysis (FRA)

Frequency response analysis (FRA) is considered to be an effective method used for detection of the mechanical integrity of transformer windings, core or contacts. The frequency range extends typically from 10 Hz to some 10 MHz (Dick and Erven, 1978). The FRA response of transformer is characterised by its inductance and capacitance distributions, which are defined by the geometry and material properties that can be regarded as a fingerprint.

If any mechanical changes occur in the transformer, for example, distorted windings, their fingerprint will also be altered. The FRA is regarded as a comparative method, in which deviations can be detected by comparing actual fingerprint with the previously obtained reference one (Tenbohlen, 2016), as Figure 11 illustrates. After that, the alterations of the frequency response are analysed to identify mechanical changes inside the transformer windings.

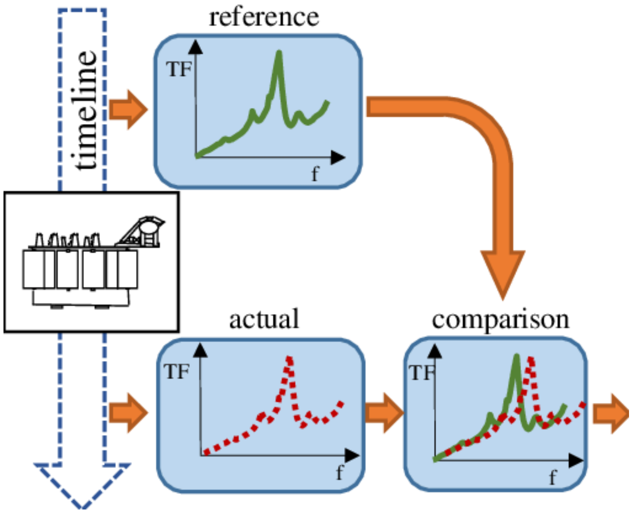


Figure 11 Block scheme of transformer winding fault analysis with FRA method

As was mentioned before, the FRA may be regarded as a comparative method. The fingerprint response from the same diagnosed transformer can be compared with the currently measured one. After comparing these two measurements with the reference set, the changes in the frequency response may be identified as mechanical defects.

Frequency response can be measured directly by sweeping the frequency or be determined from impulse response measurements. Both measuring methods possess certain advantages and disadvantages. For example, the method of impulse response requires less time for measuring but is more susceptible to external noise. On the other hand, the method of sweep frequency needs more time but is less sensitive to external noise.

While performing the analysis, several factors should be taken into consideration, such as the winding geometry, the connection system or history of defects and failures. *"Therefore, only a very experienced diagnostician can perform a correct analysis of the FRA results"* (Gawrylczyk, 2019:3).

5.3 Moisture analysis

Moisture content is considered to be a significant cause of problems in the insulation system of the power transformers. In order to avoid any incipient defects, the rate of the moisture in the insulation system must be known under all operating conditions. Moisture in the insulation system of the transformer becomes unpleasant in two respects:

- Reduces breakdown insulation voltage
- Source of oxygen in the insulation system (accelerates the deterioration of the paper)

The high moisture content can increase the risk of puncturing the insulation. The atmospheric moisture is regarded as the major source of water (Tenbohlen, 2016), which enters the transformer. The viscous flow of moist air through imperfect seals, (e.g. outlets, safety valves, cooling circuits) is believed to be the main reason for water entering the transformers. Also, large amounts of water may get inside the transformer during heavy rains if the seals are not adequately secured and at the same time the pressure inside drops. Practically all the water present in the transformer is contained in the solid insulation (over 98%) due to the strong affinity of the cellulose to water (Altmann, 2008).

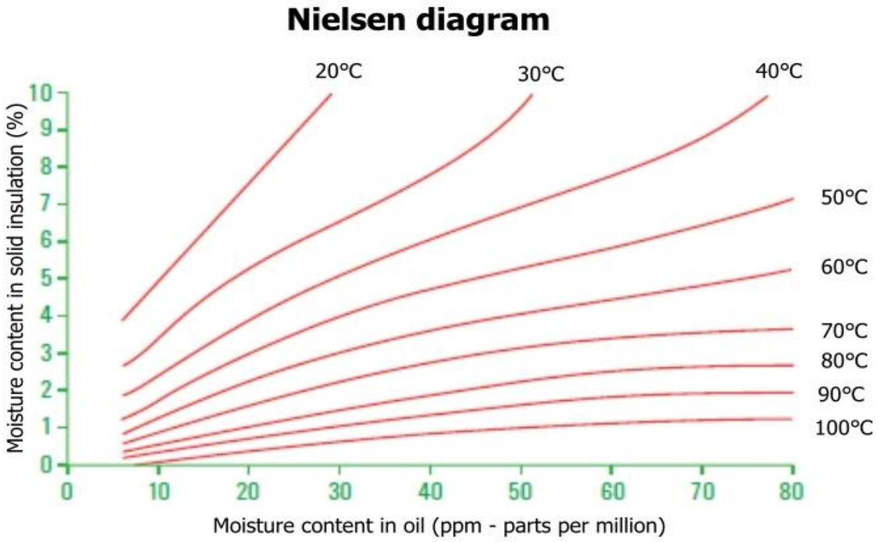


Figure 12 Nielsen diagram – Moisture equilibrium chart

The Nielsen diagram represents the equilibrium status of the moisture content in the oil at the different operational temperatures, as Figure 12 illustrates. The moisture content should be kept under 2 – 2,5% (Altmann, 2008). If the moisture level is expected to exceed 2,5%, the transformer should be dehydrated as a subject of maintenance.

The effective principle of removing moisture from the insulation is to connect a dryer to the transformer (Hanák, 2009). The dryer increases the overall temperature in the insulation due to that moisture may enter into the oil where it can be slowly removed. This method of heating and at the same time drying the transformer enhanced and shortened the current method of heating only by the usage of circulation and regeneration of the insulation oil.

5.4 Partial discharge (PD) measurement

The insulation system is subjected to electric stresses which may cause degradation of the insulation. Partial discharge (PD) is defined as local electrical discharges that only partially short-circuit the insulation system between electrodes. One of the main factors of PD in insulation is air bubbles and liquid dielectric materials. The occurrence of PD may be influenced by, e.g. inadequate treatment and impregnations in the manufacture of dielectric materials, poorly distributed electric fields, and improper application of insulation (Américo and Cabral, 2017).

PD causes a gradual deterioration of the insulation system quality, thereby reducing the electrical strength of the insulation. By measuring partial discharges, the overall degradation of the insulation system can be estimated as well as the type of discharge activity. It should be noted that transformers are never immune to the appearance of PD (Américo and Cabral, 2017) because it is impossible to manufacture them without any imperfections.

Methods for detection and measurement of PD can be generally divided into electrical and non-electric. One representative of each method is described below.

5.4.1 Electric detection method

The principle of this method is based on the insertion of the discharge detection instrument into the electrical circuit that is measured. PD, in most cases, is determined in pC (pico Columb). Detection impedance can be used for determining of an RLC (resistive, inductive, and capacitive) or RC (Havlíček, 2009). RLC is used for narrowband frequency and the RC for a band detection mode frequency. The electrical method is broadly applied for quantifying the PD. Generally, the measured electrical circuits are based on the detection of voltage drop on a known impedance, created by current pulses in the circuit outside the sample.

Analysing transformers by this method can be hampered because of the method’s complexity and inaccessibility to the internal circuits that are highly inductive. Thus, the transformers should be connected to the measuring system by the capacitive bypass of bushings. It can be performed only when the transformer is out of service.

The advantage of the electrical method involves the possibility of quantifying the intensity of the detected PD. However, the method possesses great susceptibility to electromagnetic interference (Ramírez-Nino, Pascacio, 2009), which might become a problem because the transformer environment contains high levels of electromagnetic interference, both narrowband and broadband. Furthermore, it could be challenging to distinguish between noise and PD. Ideally, this method should be undertaken in a place where external noise can be controlled, for instance, in laboratories.

5.4.2 Acoustic detection method

The acoustic method focuses on the analysis of the audible or ultrasonic noise that PD generates. In other words, the noise that propagates in the air or vibrations in materials similar to the discharge source. This method includes the use of piezoelectric sensors or transducers (Ramírez-Nino, Pascacio, 2009), which are embedded inside or outside the equipment that is measured. Acoustic methods need to observe some parameters in order to detect PD. Characteristic parameters include acoustic impedance, the velocity of propagation of the wave in the medium under surveillance.

The velocity of the acoustic signal cannot be constant as it propagates. Since the pulse of the acoustic wave is attenuated and deformed during the process. Therefore, the sensor of acoustic emission can detect only the frequency spectrum, which does not correspond to the real frequency spectrum of the source of the acoustic pulse. In the power oil transformer, the acoustic signal is generated by PD that emerges mainly as a function of streamers, which can cluster inside the gas-filled cavities (Américo and Cabral, 2017). It expands primarily due to thermal stresses, which may result in micro-explosions of mechanical energy.

The acoustic signal propagates in insulating oil, which is stored in the transformer tank, in the form of pressure waves. This process is quite similar to the formation of thunder after an atmospheric discharge. Figure 13 represents a typical acoustic wave inside the transformer.

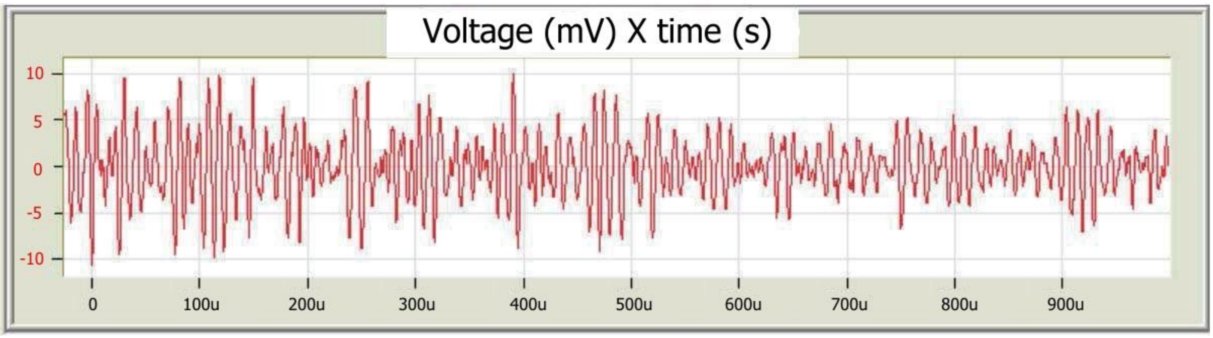


Figure 13 Typical waveform of an acoustic signal inside a transformer

Acoustic waves travel in several directions until they can be captured by the piezoelectric sensors that need to be placed appropriately on the outer face of the transformer tank (Hoek, Ranninger, 2015). Generally, for detection of the source of acoustic signals, it is assumed that the acoustic waves propagate themselves in a straight line. However, the solid insulation inside the transformer tank is composed of different sort of materials, which may represent an obstacle for the propagation way of the acoustic waves. It may even result in reflection and refraction of acoustic waves.

On the other hand, the acoustic wave can also propagate through the obstacle at a higher speed than in the oil. This means the shorter arrival time of the wave to the installed sensor, but a recorded distance will be lesser than its real value. In order to prevent such errors caused by the complexity of the acoustic wave propagation (Américo and Cabral, 2017), it is necessary to install acoustic sensors and deployed them appropriately in the transformer tank. Therefore, with more than one sensor embedded, it is possible to calculate the differences in the detection times, thereby locating the PD source.

The principle of this method is based on the in-time arrival of the sound in the sensor, which is very similar to methods used for locating earthquakes, but in three dimensions (Kundu, Kishore, 2016). Therefore, the acoustic method can detect PD activity in three dimensions that appear in the insulation system of the transformer by measuring their acoustic signals which they emitted. Figure 14 illustrates an example of the PD source location by the acoustic method.

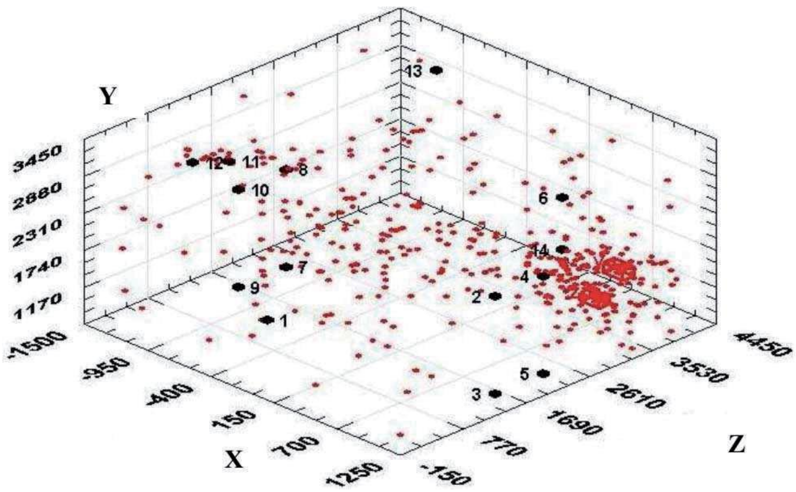


Figure 14 Location of PD source by the acoustic method

The acoustic detection method can be executed basically in two ways. The first one is performed by the acoustic composite system, which combines acoustic measurements together with the electrical signals from PD. The difference in speed and time of these two signals is determined, and after that, the distance between the acoustic sensor and the source of PD can be calculated (Américo and Cabral. 2017). The main advantage of this method is that it can detect the acoustic signal of PD and not a source of the noise. However, the main difficulty is to obtain an electrical signal free of noise during a field test. Therefore, this method is more suitable for laboratory tests.

The second one is known as a simple acoustic system. It operates with the opportunity that it is not always possible to use the electric signals in the measurement. Thus, the acoustic sensors need to be embedded on the external faces of the tested equipment. By comparing the received information from the acoustic sensors, the position of PD can be determined.

The simple acoustic system is considered to be a very attractive alternative for online PD detection due to the method’s immunity to electromagnetic interference. However, the sensors are more susceptible to external noise since mechanical vibrations in the transformer core are the main sources of the acoustic noise (Américo and Cabral, 2017). Although, these vibrations possess a smaller frequency than those generated by PD, which, allows them to be separated while the acoustic measurement is conducted.

5.5 Oil quality

Oil quality represents a good indicator of transformer condition to perform the designed functions which is to provide insulation, cooling, protection against chemical compounds and prevention of sludge formation. The oil quality can be determined by extracting and analysing samples along with comparing certain parameters against standards. The oil quality can be estimated from the following diagnostic methods: acid or neutralisation number (NN), interfacial tension (IFT), visual examination and colour.

5.5.1 Acid or neutralisation number (NN)

Acids in the insulating oil originate from oxidation products and decomposition of the oil. In addition to that, acids may also originate from external sources such as atmospheric moisture. Acids cause deterioration of the insulating oil and can also induce corrosion inside the transformer due to the presence of water. Increase in the acidity indicates the rate of deterioration of the insulating oil together with the formation of sludge as a by-product (NTT, 2019). The acid number indicates the amount of potassium hydroxide (KOH) that is required to neutralise acids contained in the gram of oil (Oelcheck). The acid number should never be allowed to exceed 0.5 mg KOH/g oil, which is the critical acid number (GlobeCore), as Table

2 indicates. Exceeding this value leads to a rapid increase in the deterioration of the insulating system, decrease in resistivity of the oil and leads to excessive oxidation, which accelerates the formation of sludge in the oil.

The acid number in oil (mg KOH/g)	**Oil status**
0.01 – 0.03	Excellent
0.05 – 0.10	Good
0.11 – 0.15	Marginal
0.16 – 0.40	Bad
0.41 – 0.65	Very bad
0.66 – 1.50	Extremely bad
Over 1.50	High risk (transformer failure imminent)

Table 2 Acid number in oil

The acid number is expressed in milligram of KOH in order to determine the required quantity for neutralisation of acids present in a specific quantity in a gram of the oil. For example, acid number in a power transformer is 0.3 mg KOH/g, which means that 0.3 milligrams of KOH are required to neutralise 1 gram of acids present in the insulating oil. The acid number can be determined by the titration method, which involves adding the oil to alcohol (1:5 ratio) with the subsequent addition of an indicator (GlobeCore). After adding alkali into the oil, it becomes either acidic, neutral or alkaline, which mainly depends on the quantity of acid present in the extracted sample. The sample is then titrated with potassium hydroxide, which leads to a neutralisation reaction of acids with alkali. The universal indicator of acid number is a chemical solution which represents several colours for different pH values of the oil. Hence the indicator colour changes during the test, the pH value of the sample can be determined by visual examination of the resulting colour (lumen). The colour of the sample indicates the value of acid number present in the oil, as Figure 15 illustrates.

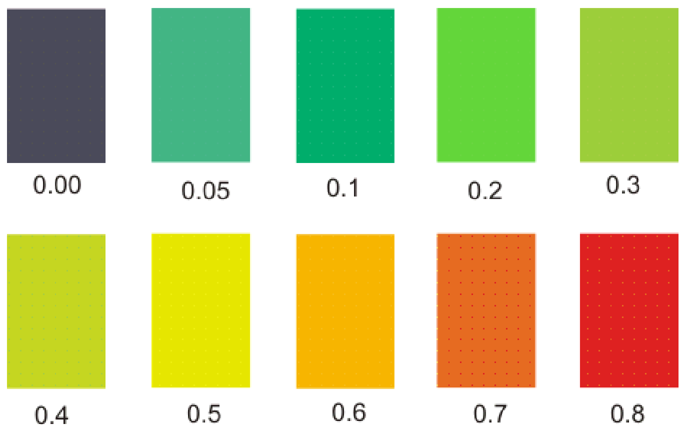


Figure 15 A colour chart for rapidly determining the acid content in insulating oil

5.5.2 Interfacial tension (IFT)

Interfacial tension is defined as the tension of the interface between two immiscible liquids (Laurén, 2017). Value of interfacial tension helps to determine the presence of polar contaminants, and in case of power transformers, it is accomplished by measuring tension of the insulating oil against water, under non-equilibrium conditions. Generally, the presence of polar contaminants lowers the value of interfacial tension. Insulating oil of the transformer needs to feature a certain interfacial tension to demonstrate that it possesses a conforming degree of quality and is free of impurities, as Table 3 indicates. Interfacial tension of the insulating oil is very sensitive to the presence of oxidation products of the oil and can be used together with acidity number as an indicator to monitor sludge formation.

Interfacial tension in oil (mN/m)	Oil status
30.0 – 45.0	Excellent
27.1 – 29.9	Good
24.0 – 27.0	Marginal
18.0 – 23.9	Bad
14.0 – 17.9	Very bad
9.0 – 13.9	Extremely bad

Table 3 Interfacial tension in oil

The interfacial tension is related to the deterioration of the insulating oil that is generally non-polar saturated hydrocarbon (Gray). However, an in-service transformer can be exposed to the oxygen, which may result in oxidative degradation of the insulating oil and as side-product of the degradation are formed oxygenated species, e.g., carboxylic acids that are hydrophilic in nature. These hydrophilic substances can negatively affect chemical (acidity), electrical (dielectric strength) and physical (interfacial tension) properties of the insulating oil (Gray). Measurement of interfacial tension provides necessary means for detecting small amounts of soluble polar contaminants and oxidation products present in the oil. Several methods can be used to determine the interfacial tension of the oil against water.

For the most recommended method of determining accurate values of the interfacial tension is considered to be the ring method (Laurén, 2017). It can be performed with a force tensiometer that is based on Du Noüy principle. This principle utilises a platinum ring that serves as a probe. The oil sample is carefully floated on the top layer of water, and due to their different densities, oil stays on the water surface. The platinum ring is then submerged below the water-oil interface (Laurén, 2017), as Figure 16 illustrates. The ring is pulled upward by force, which is needed to detach the ring from the water surface. The necessary force for detaching the ring is measured by calibrated torsion wire and is used to calculate interfacial tension between water and oil (Gray). Measurement is performed within 60 seconds after the formation of the water-oil interface, with the tensiometer determining the value of interfacial tension. Results are expressed in mN/m (milli Newtons per meter) or dynes/cm.

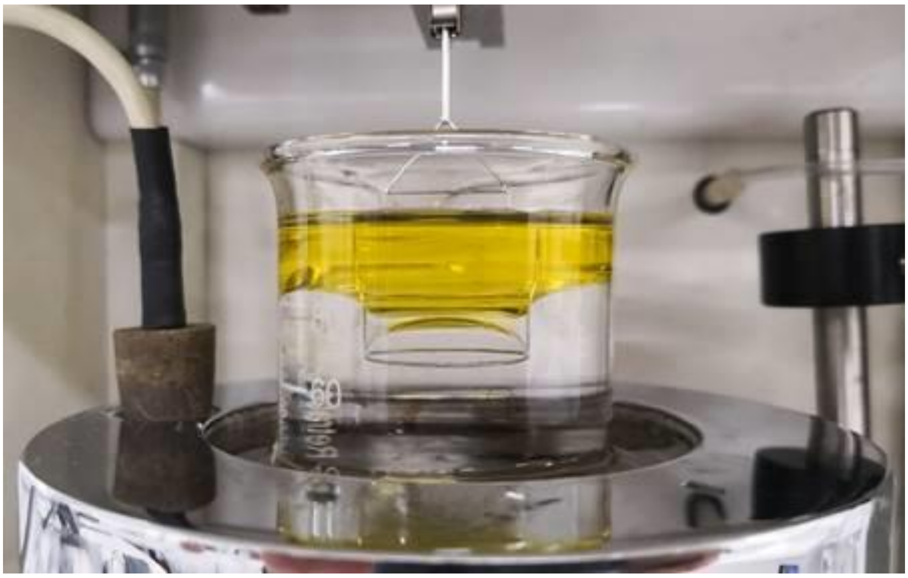


Figure 16 Force tensiometer measuring interfacial tension between water and oil by the Du Noüy ring method

The high value of interfacial tension (40 mN/m and more) indicates the absence of polar contaminants in the insulating oil, which means that it is immiscible with water (Gray). In contrast, a decrease in interfacial tension results in higher accumulation of contaminants or oxidation products and enables the oil to mix with water. In addition to that, there are correction factors that need to be considered before measurement and are related to densities of water and a sample along with the platinum ring, which needs to be made in precise dimensions.

5.5.3 Visual examination and colour

Insulating oils tend to change colour during transformer operation, especially when oil ages, it slowly transforms from pale yellow to brown or black colour (Ramanathan, 2018). Colour can be changed because of the presence of contaminants, e.g., water, oxidation products, gases, sludge, as well as degradation and ageing. Therefore, oil darkening serves as a sign for that oil needs to be changed or filtered. Insulating oils need to be filtered or changed at least every six months periodically in order to prevent any incipient defects that may occur during transformer operation, e.g., arcing, corona discharges, overheating, or decreased strength of the insulation (Ramanathan, 2018). Monitoring and testing colour of insulating oil is considered to be one of the easiest methods for determining the exact age of oil along with whether or not still fulfils designed features. It is also an essential part of maintaining the fault-free operation of transformers.

Analysis of oil colour is performed according to internationally recognised standard ASTM D1500. The standard is used not only for analysing the colour of transformer oils but also to a wide variety of petroleum products. Colour of oil is graded on the scale, which ranges from 0.5 to 8 with the step of 0.5, as Figure 17 indicates.

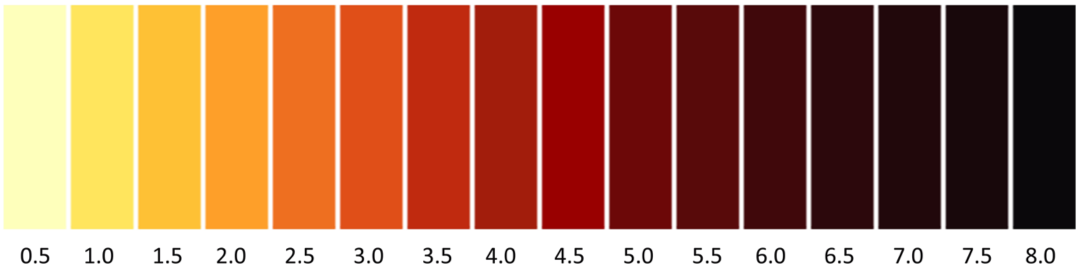


Figure 17 ASTM Colour scale value

ASTM colour value is determined by an online device that provides the accurate and fast result and allows quick reaction to any sudden changes in oil quality. In addition to that, analysis can be conducted at multiple sampling spots simultaneously, which helps to find a source of oil quality change more easily (Kytola).

5.5.4 Oil quality index (OQIN)

As oil ages, it becomes slowly contaminated by tiny particles that are the result of deterioration of the oil together with paper insulation. These particles tend to weaken interfacial tension, which may indicate the beginning of sludge formation. Usually, when the value of interfacial tension falls to 25 mN/m, it is recommended to reclaim the oil in order to prevent sludge settling on inner transformer parts, e.g., windings, insulation, thereby causing cooling and loading problems (Chowdary, Singh, 2014). These problems can significantly shorten the lifecycle of the transformer. Interfacial tension together with Acid or neutralisation number serves as an excellent indicator of whether or not insulating oil needs to be reclaimed. Figure 18 represents the limits of normal service for both.

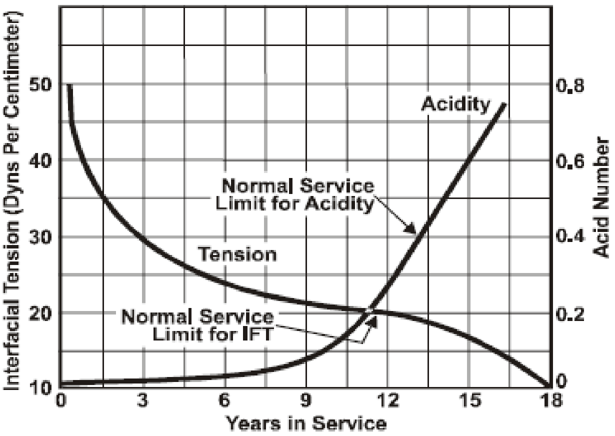


Figure 18 Relationship between acid number and interfacial tension

The acid content in the oil rises naturally as transformer ages. Acids accelerate the degradation of the insulation system and induce corrosion inside the transformer along with the formation of sludge, which begins when the acid number reaches the value of 0.40 mg KOH/g (Chowdary, Singh, 2014). It is more than recommended that the oil should be reclaimed before it reaches this value. A preferred value for reclaiming oil is 0.20 mg KOH/g (Chowdary, Singh, 2014).

Interfacial tension divided by acid number provides a numerical value that can determine the condition of oil. The numerical value is known as oil quality index (OQIN) or Myers index number (MIN) and is defined by the following relationship between interfacial tension and acid number (Gray).

$$OQIN = \frac{IFT}{NN}$$

The result obtained from this relationship indicates the value of the oil quality index of the analysed power transformer. In order to determine the condition of the oil, the value of OQIN needs to be compared with the estimated values of transformer oil classifications, which are represented by Table 4 below.

Classifications	**Oil quality index (OQIN)**
Good oils	300 - 1500 (Pale yellow colour)
Proposition A oils	271 - 600 (Yellow)
Marginal oils	160 - 318 (Bright yellow)
Bad oils	45 - 159 (Amber)
Very bad oils	22 - 44 (Brown)
Oils in disastrous condition	< 5 (Black)

Table 4 OQIN as per the Gray chemical analysis

5.6 Evaluation of solid insulation

The mechanical properties of solid insulation can be determined by direct measurement of either tensile strength or degree of polymerisation (DP) (Gray, 2017). The value of these parameters can be used to evaluate the remaining life of solid insulation. It is mostly suggested that DP values of 150-250 may indicate lower limits for end of life criteria for the solid insulation (Powertechlabs).

DP value of the solid insulation can be estimated by removing of few strips of insulating paper. Nevertheless, the procedure can be conducted only when transformers are out of service. Therefore, the direct measurement of these parameters is not very practical for in-service transformers. In addition to that, the process of removing the paper is rather difficult, especially if an analysed transformer is expected to continue in service (Mtetwa). This procedure may even result in transformer failure if it is not performed with appropriate skill. Thus, the ability to determine the condition of the insulation paper without exposing transformers to risks of this kind is very desirable.

According to several studies, the DP value of solid insulation can also be estimated by indirect testing that can be performed by analysing the concentration of furanic compounds present in the oil (Mtetwa). These furanic compounds are formed mainly during the ageing process of the insulation paper. The furanic compounds migrate after their formation from paper into the oil. Therefore, by analysing the oil for the presence of furans, the DP value can be estimated.

5.6.1 Furan analysis

The furan analysis represents an alternative method for determining the DP value of paper insulation that is considered to be non-intrusive (Mtetwa). Furans can be defined as chemicals that are formed due to the degradation of cellulose paper insulation. The insulating paper does not age uniformly, and the condition of the paper is expected to differ due to temperature, moisture, oxygen levels and other conditions under which transformers operate.

The main reason why the furan analysis is preferred to carbon-oxide gas analysis is that carbon-oxides are not only formed during ageing of paper insulation but also as the result of partial discharge and overheating. In contrast, furanic compounds are mainly generated due to thermal ageing, especially when transformers are exposed to very high temperatures during their service, typically above 120°C, which leads to higher accumulation of furanic compounds in the oil (Mtetwa). Furans may also be formed in small quantities when cellulose paper is subjected to partial discharges. Therefore, furans that are dissolved in insulating oil may be regarded as an important sign of thermal and mechanical degradation in oil-paper insulation (Chen, Gu, 2016).

As insulating paper within transformers ages, it may lead to the production of chain furanic compounds. Once formed, furans can survive for long periods of time in insulating oil, which is at spots with a lower temperature than in hottest spot in insulation (windings) (Mtetwa). Table 5 represents typical furan compounds that can be formed.

Furanic compounds	Formulas	Interpretation
5-Hydroxymethyl-2-furaldehyde	5H2F	Oxidation
Furfuryl alcohol	2FOL	High moisture
2-Furaldehyde	2FAL	Overheating
2-Furfuryl methyl ketone	2ACF	Sparking
5-Methyl-2-furaldehyde	5M2F	Severe overheating

Table 5 Typical furan compounds

However, some furanic compounds are not stable in the insulating oil and analysing their quantities may lead to an inaccurate conclusion (Mtetwa). Some of the furans mentioned above can be very unstable. Therefore, these furanic compounds cannot be used for diagnostics. Nevertheless, several studies revealed that 2-furaldehyde (2FAL) is the most stable furan compound of cellulose ageing and is directly related to the DP value of insulation paper (Gray). High concentrations of the 2-furaldehyde, usually the most prominent compound, present in the oil can serve as an indication of the average deterioration of the paper (Gray, 2017). The overall DP value of solid insulation can be, therefore estimated through this relationship with a high degree of confidence, as Table 6 indicates.

2-Furaldehyde content (ppm)	DP value	Interpretation
0 – 0.1	1200 – 700	Healthy transformer
0.1 – 1.0	700 – 450	Moderate deterioration
1 – 10	450 – 250	Extensive deterioration
>10	< 250	End of life criteria

Table 6 Values of 2-furaldehyde for typical power transformers and their significance

The concentration of furanic compounds in the oil can be determined by two methods: screening test or high-performance liquid chromatography (HPLC) test. The principle of the screening test is based on the colour analysis through which can be measured only concentration of 2-furaldehyde. In contrast, the HPLC test can provide a complete analysis of furans and phenols, and this is the main reason why is mostly preferred before the screening test.

6 Practical part

The practical part of the thesis focuses on the analysis of the chosen power oil transformer and estimating the condition of the insulation system. The set of diagnostic methods is proposed for the measurement of the values of selected parameters concerning the insulation system. The procedure of each diagnostic method is described, and possible causes of defects are discussed together with countermeasures, which are suggested. The proposed diagnostic methods are the following: Gas chromatography, Acidity test, Du Noüy ring method, Colour analysis and High-performance liquid chromatography. Unfortunately, because of the Covid-19 situation, it was impossible to obtained data to all parameters mentioned in the theoretical part of the thesis.

The chosen power oil transformer for the analysis is used to interface step-down voltages in a thermal power plant located in the Czech Republic. Table 7 represents the parameters of the chosen power transformer.

Type of transformer	Oil-immersed
Type	53T172/104
Manufacturer	ČKD Praha
Power output	25 000 kW
Year of manufacture	1975
Primary/secondary windings	15.75/6.3
Phase connection	Delta
Vector group	Dd0

Table 7 Technical data of the analysed power oil transformer

6.1 Methodology

In the practical part of the thesis, the set of diagnostic methods was proposed for measuring values of the selected parameters concerning the state of the insulation system of the chosen power oil transformer. Some of these methods are already utilised in practice, and the rest may offer more advanced techniques and equipment, which could be useful in obtaining more accurate and faster results. After that, values of the selected parameters were analysed from which, the condition of the insulation system was determined. The measured data were provided by the company I&C Energo and were obtained from the information system, which supports the management of ageing technological systems and is known as LTO Suite (Long term operation). LTO Suite is designed to provide tools for administration, storage and mainly for evaluation of diagnostic data, which are related to specific types of equipment. The diagnostic data selected for the analysis were obtained in the form of protocols.

After the selection of diagnostic methods, their main features and benefits were described together with apparatus and equipment needed for the analysis and procedure of the measurement was presented. Procedures of these methods were described in detail, including their sampling methods. The measured data were then compared against standards, which helped to determine whether or not the values corresponded with recognised limits for safe and reliable operation. The results from these comparisons enabled to estimate if the values of selected parameters were within the range of acceptable limits or not. In addition to that possible causes of defects were discussed together with countermeasures, which were proposed in order to maintain the good condition of the insulation system.

The selection of diagnostic methods was based on the search for the most suitable methods for measuring the selected parameters, which can provide reliable, accurate and relatively fast results, which is very desirable in order to detect incipient defects faster and prevent any unwanted outages. Some of these methods are already frequently utilised in practice. However, because of the Covid-19 situation, it was impossible to obtain data to all previously intended parameters. Therefore, the analysis focused only on evaluating the condition of the insulation system.

6.2 Selected diagnostic methods

6.2.1 Gas chromatography

Gas chromatography is a highly efficient method for analysing dissolved gases in the transformer oil and is able to provide reliable information about the condition of transformers. This method can offer several features, e.g., speed of analysis, moderate costs, separation of complex mixtures and accurate quantitative results. Due to these facts, the gas chromatography can be referred to as one of the most versatile techniques and is frequently used for monitoring transformers.

The basic principle of the analysis is based on the ability of the insulating oil to dissolve not only the ambient air but also decomposed gases. The decomposed gases may evolve from natural ageing of the oil and cellulose materials in the insulation but in most cases, as the result of thermal and electrical stresses that appear in transformers. Therefore, from trend analysis and concentration of dissolved gases in the oil, the source of the defect can be identified.

The measurement is conducted by the usage of a gas chromatograph. The instrument is divided into several units vis page 23. Figure 19 illustrates a typical gas chromatograph. The gas chromatograph distributes compounds of an extracted sample between two phases: mobile and stationary. Due to different affinities of individual compounds for either stationary or mobile phase, a resulting retention time varies for each compound. A corresponding chromatogram determines the total concentration of dissolved gases in the oil.

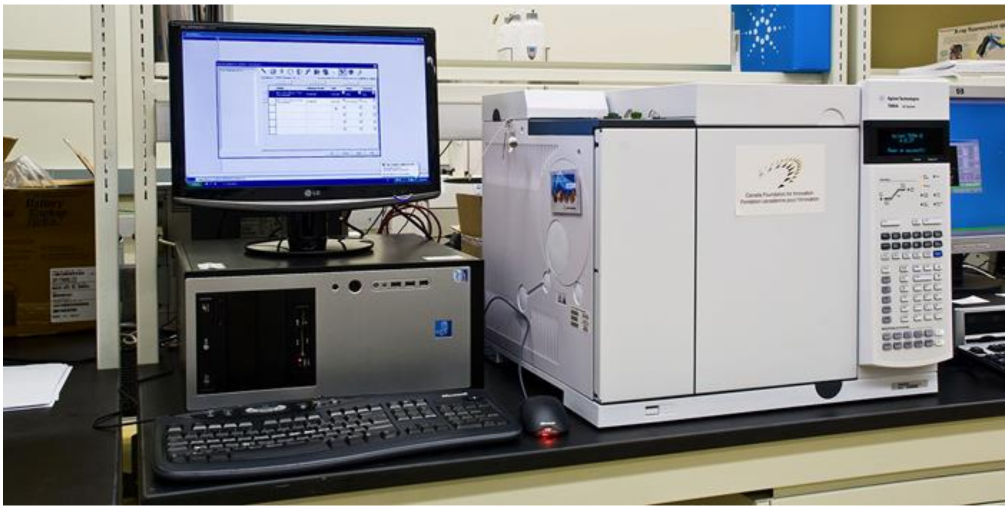


Figure 19 Gas chromatograph

Before the analysis is performed, the sample is derivatised to increase volatility, sensitivity, improve separation and reduce thermal degradation and tailing (Oelcheck). The oil sample is extracted by a syringe from the in-service transformer, and in order to ensure correct results, the extracted sample must not come into contact with the ambient air. Therefore, immediately after the extraction, the sample is poured into 20 ml gas-tight syringe made of glass and flushed with argon to remove air and send to a laboratory. From the sample, 5 ml are extracted and injected through a cannula into the injection port of the gas chromatograph. The temperature in a sampler is set to 80℃ through which, the gases are expelled from the extracted sample and gradually heated in an oven up to 200℃. The vaporised gases are flushed with the help of carrier gas through a column to be separated. The gases are separated in the column, and due to their different structures, each gas remains in the column for a different period of time. The retention time at which, individual gases leave the column, is recorded by a detector in the form of corresponding chromatograms. From an area under a peak of the chromatogram, the proportion of the individual gases in the sample is concluded. Table 8 represents the measured concentration of the gases in the analysed power transformer.

Gases	**Concentration (ppm)**	**Complies with IEEE limits**
Hydrogen ($\boldsymbol{H_2}$)	20.8	Yes
Methane ($\boldsymbol{CH_4}$)	2.0	Yes
Ethane ($\boldsymbol{C_2H_6}$)	0.8	Yes
Ethylene ($\boldsymbol{C_2H_4}$)	7.4	Yes
Acetylene ($\boldsymbol{C_2H_2}$)	3.4	Yes
Carbon monoxide ($\boldsymbol{CO}$)	75.6	Yes
Carbon dioxide ($\boldsymbol{CO_2}$)	901.0	Yes

Table 8 Concentration of dissolved gases in the analysed power transformer

Results

The concentration of individual gases now needs to be compared with IEEE limits vis page 24 in order to determine the condition of the insulating oil. According to the gassing rates, the analysed transformer definitely experienced overloading during operation due to increased concentration of carbon oxides present in the oil. The higher concentration of these gases could be the result of thermal stresses possibly caused by overload operation for a short period of time. The rate of carbon monoxide along with hydrogen may also be an indication of cellulose degradation due to overheating or arcing. The rest of the gases correspond with regular gassing rates in an in-service transformer. Since the analysed power transformer already exceeded designed lifecycle, it can be concluded that the insulating oil is in very good condition and is capable of performing the designed functions. However, it is necessary to emphasise that the development of dissolved gases is expected due to the natural ageing of the insulating oil. Therefore, periodical monitoring and testing are more than recommended in order to preserve the good condition of the insulating oil and eventually plan oil reclamation at the right time.

6.2.2 Acidity test

Acidity test represents a simple and quick test for detecting acid content in the insulating oil. It is performed by the titration method vis page 33, and it can be conducted directly on the spot. The resulting reaction of titration method is indicated by a colour change of an extracted sample and compared with a colour chart vis page 35 to determine the necessary quantity of potassium hydroxide (KOH) needed to neutralise the acid content in the insulating oil.

Several substances are needed in order to measure the acid content in the transformer oil including potassium hydroxide (KOH), a sample of oil, ethyl alcohol, sodium carbonate solution and universal indicator in a test tube (Powerlink, 2018). First, it is necessary to extract exactly 1.1 millimetres of the insulating oil into the test tube through volumetric syringe or dropper. After the extraction of the sample, 1 gram of ethyl alcohol is added in the sample and gently shake with it. After shaking the sample, 1 millimetre of sodium carbonate is mixed with the sample. The sample is shaken again, and 5 drops of the universal indicator are added in the solution. The solution changes the colour and indicates the acid content in the insulating oil of the analysed power transformer. Table 9 represents the value of the acid number of the insulating oil determined by the colour chart.

Acid number	0.1 mg KOH/g

Table 9 Acid number of the analysed power transformer

Results

The resulting value of the acid number indicates that exactly 0.1 milligrams of KOH is required to neutralise 1 gram of acids present in the insulating oil of the analysed power transformer. From the resulting acid number can be concluded that the rate of deterioration of the insulating oil together with the formation of the sludge is low. Therefore, according to Table 2 vis page 34, the oil can be considered to be in good condition concerning the total level of the acidity. The possible cause of the acids in the oil might be the fact that the analysed power transformer is exposed to the ambient air and moisture during service, which may result in gradual oxidation and decomposition of the oil. Thus, the insulating oil should be analysed at regular intervals in order to ensure the fault-free operation and prevent an increase in the deterioration of the oil together with the formation of sludge.

6.2.3 Du Noüy ring method

The Du Noüy ring method is the most frequently used technique for determining accurate values of interfacial tension of pure liquids and solutions. It is performed with a force tensiometer, which is based on Du Noüy principle. The principle utilises a platinum ring that serves as a probe vis page 35. The force tensiometer is designed to perform high-precision, automatic and reliable measurements of interfacial or surface tension (kruss-scientific). The instrument utilises a force sensor with high resolution that ensures accurate and reliable measurements and is able to detect force changes down to 0.001 micro-Newtons. It can be configurated with different types of measuring probes, e.g., the Du Noüy ring, the Wilhelmy plate and the Wilhelmy rod. Figure 20 illustrates a modern force tensiometer.

Figure 20 A modern force tensiometer

The Du Noüy ring method is based on the principle of measuring a maximum force that liquid places on the platinum ring. The fully automated measurement starts with pouring the oil on the top layer of water and waiting 30 seconds for the interface to be stabilised. The whole measurement is conducted within 60 seconds after the stabilisation of the water-oil interface. The ring is then suspended from the force sensor and slowly submerged below the water-oil interface. The system automatically detects the surface position, and after wetting, the ring starts to approach the surface gently with the help of an extremely precise lift. The maximum force is detected and measured by a calibrated torsion wire, from which the system software calculates the interfacial tension between water and oil. Table 10 indicates the calculated value of the interfacial tension of the analysed power transformer.

Interfacial tension	44 mN/m

Table 10 Interfacial tension of analysed power transformer

Results

The calculated value of the interfacial tension, according to Table 3 vis page 35, indicates the absence of undesirable polar contaminants in the insulating oil. From the calculated value can be concluded that the oil possesses the conforming degree of quality and is free of impurities. The value of the interfacial tension decreases gradually due to the ageing process and accumulation of oxidation products in the oil. The low value of the interfacial tension may result in functional failure and in the worst scenario, even in an explosion. Therefore, the measurement should be performed at regular intervals in order to ensure the fault-free operation and plan the oil reclamation at the right time.

6.2.4 Colour analysis

Colour analysis provides a rapid assessment of insulating oil quality. Instruments known as oil colour analysers are used to conduct the colour analysis of the insulating oil, as Figure 21 illustrates. The online instrument is based on the principle of visible light absorbance, which provides ASTM colour value of the oil according to which, the oil quality can be estimated. The online measurement allows a fast and continuous response to any sudden changes in the quality of the insulating oil. Due to the usage of the online instrument, the testing procedure is faster and less expensive than sampling and laboratory analyses.

Figure 21 Oil colour analyser

Before the oil sample is analysed, a reference detector is used to compensate differences in lighting conditions by detecting light intensities, thereby ensuring more accurate results. The oil sample is then backlighted by three-colour LED (one colour at a time) with two visual light detectors, which measure light intensities that are emitted by the LED. The colour value is obtained by a measuring detector that determines intensities of light, which are transmitted through the oil sample. Table 11 represents the colour value of the oil.

Colour value	1.1

Table 11 Colour value of the insulating oil in the analysed power transformer

Results

The measured value needs to be compared with the ASTM Colour scale values vis page 37 in order to determine the colour of the insulating oil of the analysed power transformer. From the value of colour can be concluded that the colour of the insulating oil is yellow. The yellow colour indicates that the oil is clearly without any traces of contamination and can be referred to as fresh oil. Therefore, the insulating oil is cable of performing the designed features. The change of colour occurs mainly due to ageing process of the oil, so oil darkening can serve as a good indicator for planning the oil reclamation or filtration from contaminants that may be present due to degradation or oxidation of the oil. In addition to that, the exact age of the oil can be easily estimated from the colour of the oil and whether or not still fulfils designed features.

6.2.5 High-performance liquid chromatography

High-performance liquid chromatography (HLPC) is the most frequently used method for analysing furan compounds in the insulating oil. Unlike the screening test, which can only measure the concentration of 2-furaldehyde, the HPLC tests provide a complete analysis of furans and phenols. In comparison with standard liquid chromatography, the HLPC utilises smaller, narrower columns, which enables faster separation of analytes. The faster separation is achieved with the help of high pressure provided by a pump, which is used to force the mobile phase and analytes through columns. The usage of high pressure ensures effective and faster separation.

Unlike the previous form of liquid chromatography, specialised apparatus is needed for HLPC separation due to the presence of high pressures (up to 700 bar) in the column. Due to this fact, equipment of the HLPC must be of high quality. Therefore, it is more expensive than in the case of the standard liquid chromatography. Sampling is fully automated and controlled by computer. However, manual injection of a sample is still possible, but it is less frequently used. Figure 21 illustrates the high-performance liquid chromatograph.

Figure 22 High-performance liquid chromatograph

The procedure starts with extracting the oil sample form in-service transformer. The sample is sent to a laboratory, where it is absorbed in a few millimetres of pentane. After the sample is absorbed, furan and furaldehyde derivates are separated through solid-phase extraction. An auto-sampler introduces a few microliters of the sample to the flow of eluent from a mobile phase to a separation column under a constant high-pressure generated by a pump. Analytes are separated inside the column due to their various polar interactions with column packing and remain on a stationary phase of the column with different degrees of force. Therefore, the sample is divided into individual analytes. The individual analytes gradually elute, and their concentration is recorded by UV absorption detector at characteristic retention time as they leave the column. Table 12 indicates the concentration of furan compounds in the insulating oil of the analysed power transformer.

Furan derivates	**Content (ppm)**
Hydroxymethyl-2-furaldehyde (5H2F)	0
Furfuryl alcohol (2FOL)	0.01
2-Furaldehyde (2FAL)	0.61
2-Furfuryl methyl ketone (2ACF)	0
5-Methyl-2-furaldehyde (2M2F)	0.06

Table 12 Measured concentration of furan compounds

Results

From the detected concentration of 2-furaldehyde in the insulating oil can be concluded vis page 41 that the solid insulation is in the state of moderate deterioration. The degree of polymerisation is determined by the value ranging from 700 to 450 and can be considered to be still far from the critical point. According to this value, the paper ageing can be regarded as mild to minimal, which means that the solid insulation can still fulfil the designed functions efficiently. The higher concentration of 2-furaldehyde can be the result of thermal stresses possibly caused by overload operation for a short period of time, which could lead to higher accumulation of furanic compounds in the oil due to increased temperatures during operation. This claim can be supported by already increased concentration of carbon monoxide vis page 45, which may also be the result of thermal stresses. Therefore, analysis of furan derivates should be performed at regular intervals in order to know the condition of the solid insulation and ensure fault-free operation.

Conclusion

The thesis aimed to describe the process of life management together with degradation mechanisms, which are influencing lifecycle of in-service power oil transformers. The process of life management is utilised as the necessary mean for securing the safe and reliable electric power supply. The electric power transmission and distribution is significantly influenced by the reliable operation of power oil transformers that belong to one of the most important elements in the electrical grid. Therefore, fault-free operation of power transformers is the subject of the major economic importance, especially for power supply utilities that need to ensure safe and reliable electric power supply to end-consumers. In the current economic climate, power supply utilities often tighten their control over the capital budget and make cutbacks in maintenance. Present units often need to endure overload operations, which may result in deferring investment into additional power plan capacities. Due to this fact, the condition of power transformers can be negatively affected by additional mechanical, thermal and electrical stresses and increase the probability of failure, especially when transformers already exceeded designed lifecycle. Financial expenses due to unexpected transformer failure can exceed its initial price several times over, which also includes charges for not providing enough electrical power to end-consumers. Therefore, power transformers need to be subjected to continuous monitoring and testing at regular intervals, which is achieved by the implementation of technical diagnostics and diagnostic methods that are an essential part of the process of life management. The technical diagnostics, along with diagnostic methods, provide an effective way of ensuring safe and reliable operation of power transformers.

The practical part of the thesis focused on the analysis of the chosen power oil transformer and estimating the condition of the insulation system. In addition to that, the set of diagnostic methods was proposed for the measurement of selected parameters, which could provide more accurate and faster results with the utilisation of advanced techniques and equipment. The analysis of the insulation system was based on measured data obtained from the information system LTO Suite in the form of protocols and focused on the following parameters: dissolved gases in the oil, interfacial tension, acid content, the colour of the oil and furan compounds.

From the composition of gases in the oil can be concluded that the analysed transformer experienced overload operation due to increased rates of carbon oxides, which originate mainly due to thermal stresses. The total acid number indicates that the rate of deterioration of the oil, together with the formation of sludge is low. The acidity is expected to rise since the analysed transformer is exposed to the ambient air and moisture during service, which eventually may result in gradual oxidation and decomposition of the oil. The value of the interfacial tension implies that the oil possesses the conforming degree of quality and is free of impurities. The interfacial tension decreases gradually due to the ageing process and accumulation of oxidation products. The colour of the oil is estimated by the measured value and can be regarded as yellow, which indicates that the oil is clearly without any traces of contamination. From the concentration of 2-furaldehyde in the oil can be concluded that the condition of the solid insulation is in the state of moderate deterioration. The state of moderate deterioration indicates that the paper ageing can be determined as mild to minimal according to the estimated degree of polymerisation ranging from 700 to 450, which is still far from the critical point. The higher concentration of 2-furaldehyde can be the result of thermal stresses possibly caused by overload operation. From all of these results can be concluded that the condition of the insulation system is good and capable of performing the designed features. However, it is more than recommended for the analysed transformer to be further monitored and tested at regular intervals, mainly due to the fact that it already exceeded the designed lifecycle.

Some of the methods, which were suggested for the measurements, are already frequently used in practice due to their ability to provide reliable and relatively fast results, which helps to react more quickly to any sudden changes in the state of analysed parameters. Most of these methods are performed fully automatically with the utilisation of advanced equipment in laboratories, which contributes to more precise and faster measurements. In combination with other methods that focus on the rest of the transformer parameters, it is more than possible to ensure fault-free operation if the continuous monitoring and testing are implemented at regular intervals, thereby contributing to the extension of the transformer lifecycle.

The process of life management represents an essential instrument for power supply utilities for securing safe and reliable electric power supply together with reducing potential technical and economic losses caused by unexpected transformer failure.

Rozšířený abstrakt

Tato bakalářská práce představuje proces řízení životnosti, který se v tomto případě soustředí na výkonové olejové transformátory. V teoretické části je popsána funkce a role výkonových transformátorů v elektrizační soustavě. Dále je zde popsán proces řízení životnosti, kde jsou zmíněny hlavní výhody tohoto procesu spolu s jeho hlavními částmi, které zahrnují technické diagnostiky a diagnostické metody. Praktická část se soustředí na zhodnocení stavu izolačního systému vybraného výkonového olejového transformátoru za využití diagnostických metod zmíněných v teoretické části práce.

Výkonové transformátory mají nezastupitelnou roli v procesu přenosu, distribuce a využívaní elektrické energie. Transformátory jsou elektrické netočivé stroje, které pracují na principu elektromagnetické indukce. Výkonové transformátory se používají ke zvýšení nebo snížení hladin střídavého napětí v elektrických sítích a tím snižují ztráty vzniklé během přenosu elektrické energie. Provedení transformátorů je dáno hlavně způsobem jeho chlazení, které se dělí na dva typy olejového a vzduchového chlazení. Olejové chlazení je nejčastěšjím typem, který se používá v elektrizační soustavě od výrobního zdroje až po konečnou distribuci. Suchý typ transformátorů se více využívá ve vnitřních prostorech, kde nehrozí riziko požáru způsobené vzplanutím izolačního oleje. A protože je olejový typ nejčastěji využívaným typem výkonového transformátoru, tak na něj bude zaměřen proces řízení životnosti.

Výkonový olejový transformátor představuje klíčový prvek a náhlá ztráta jeho funkčnosti může způsobit výpadek výrobního bloku a tedy přerušit dodávku elektrické energie. Obnova tohoto typu zařízení je finančně velmi náročná a může převýšit i počáteční investici za nový stroj. Toto jsou hlavní důvody proč je potřeba směřovat pozornost k výkonovým olejovým transformátorům z hlediska údržby a provozování, ale také z pohledu diagnostiky a určení možných poruch. Velmi důležitým údajem pro řízení údržby, je informace o současném technickém stavu zařízení a zjištění příčiny poruchy během jeho provozu. Tyto informace o stavu zařízení zajišťuje technická diagnostika, jejíž metody jsou zaměřeny na jednotlivé části transformátoru. Technická diagnostika je rozdělena na offline a online. Offline diagnostiky se provádějí v pravidelných intervalech většinou na odstaveném stroji se zaměřením na určité parametry, např: voda v oleji, měření číslo kyselosti a měření hladin částečných výbojů. Online diagnostiky se naopak spíše používají k měření základních veličin, např: napětí, proud a obsah plynů v oleji. Největší výhoda online diagnostik je ta, že je zařízení neustále monitorováno za použití senzorů, které jsou umístěny přímo na zařízení. Data jsou tedy automaticky vyhodnoceny a nahrána do systému, což přispívá k rychlé detekci nežádoucích poruch.

Tyto nežádoucí poruchy, též zvané jako degradační mechanismy, jsou běžnou součástí životního cyklu výkonových transformátorů a ovlivňují jejich sledované parametry. Za nejvýznamnější parametr se považuje funkce izolačního systému, která je do velké míry ovlivněna elektrickými, tepelnými a mechanickými stresy, které mohou způsobit zkrácení celkové životnosti zařízení. Právě kvůli tomu byl izolační systém vybrán pro zhodnocení jeho stavu u vybraného výkonového olejového transformátoru za použití diagnostických metod, které se zaměřují na sledovaní parametrů izolačního systému papír/olej.

Praktická část této práce se zaměřuje na zhodnocení stavu izolačního systému u vybraného výkonového olejového transformátoru na následující parametry: plyny rozpuštěné v oleji, číslo kyselosti, povrchové napětí, barva oleje a furanové deriváty. Pro měření těchto parametrů byly navrženy diagnostické metody, které by mohly poskytnout přesnější a rychlejší výsledky za využití pokročilých technik a přístrojů. Data pro tyto parametry byly poskytnuty ve formě protokolů z informačního systému LTO Suite. Diagnostické metody pro účel analýzy těchto parametrů byly vybrány na základě jejich spolehlivých výsledků a častého využití v praxi. U každé z těchto metod byly představeny výhody, popis aparátů a vybavení potřebných k měření, detailnímu popisu postupu jednotlivých metod a interpretace jejich výsledků. Na základě výsledků diagnostických metod byl u každé zhodnocen stav daného parametru, určeny možné příčiny ovlivňující jeho stav. Dále byly navrženy možné protiopatření, které by bylo možné implementovat za účelem udržení funknčního stavu jednotlivých parametrů.

U analyzovaného výkonového olejového transformátoru byly díky výsledkům z diagnostických metod pozorovány změny v obsahu rozpuštěných plynů v oleji, kde se zjistila vyšší koncentrace oxidu uhelnatého a oxidu uhličitého. Zvýšená koncentrace těchto plynů naznačuje, že analyzovaný transformátor byl vystaven po určitou dobu přetížený, které mohlo vyvolat zvýšené pracovní teploty, při kterých se pravděpodobně zvedla koncentrace těchto dvou plynů. Číslo kyselosti bylo mírně zvýšené, ale stále se nacházelo v přijatelných hodnotách, podle kterých bylo určeno, že degradace oleje a tvorba sedimentů je nízká. Dále byla určena velice dobrá hodnota povrchového napětí, což znamená, že olej je nemísitelný s vodou a neobsahuje žádné nečistoty. Vzhledem k barvě oleje, jež byla určena jako žlutá, může být olej považován za čerstvý. Jako poslední byla pozorována zvýšená koncentrace furfuralu v oleji, podle které lze určit, že pevná izolace utrpěla mírnou degradaci. Polymerační stupeň pevné izolace je ale pořád daleko od dosažení kritické hodnoty. Celkový stav izolačního systému papír/olej ukazuje na mírnou degradaci, ale jinak je schopný plnit bezpečně všechny funkce.

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Stock Photo - Force tensiometer measuring interfacial tension between water and oil by the Du Nouy ring method. Laboratory equipment for scientific research in nanotechnology and colloid chemistry. In: *123rf* [online]. [cit. 2020-04-25]. Dostupné z: https://www.123rf.com/photo_113300185_force-tensiometer-measuring-interfacial-tension-between-water-and-oil-by-the-du-nouy-ring-method-lab.html

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